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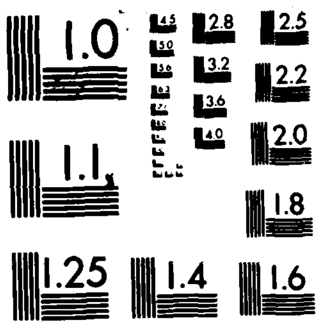

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MRL-R-905

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E.H. van Leeuwen

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NOVEMBER, 1983

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The asymptotic formulae of the surface displacement are derived in the limit as $r, t \rightarrow \infty$, using the method of stationary phase.

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ABSTRACT

This paper discusses wave propagation in the far field due to an underwater disturbance. The driving mechanism of the disturbance is taken to be a cylindrical volume of water projected vertically under the action of ordinary forces. Particular emphasis is placed on achieving a closed form solution to Laplace's equation.

The asymptotic formulae of the surface displacement are derived in the limit as $r, t \to \infty$, using the method of stationary phase.

CONTENTS

LARGE AMPLITUDE WAVES GENERATED BY AN EXPLOSIVE MECHANISM

1. INTRODUCTION

During the period 1946 to 1958 a series of observations were made of waves formed by detonating nuclear devices below the ocean surface. Because the effects of deep underwater nuclear explosion are largely of military interest, phenomena associated with these tests are not well documented in the open literature.

For a nuclear device detonated in deep water, the wave intensity is represented by the peak-to-peak height H of the wave envelope. The manner in which the height diminishes with distance or radius R from surface zero has empirically been found to be (Glasstone and Dolan (1977)):

$$H \sim 4.36 \times 10^5 W^{.54} R^{-1}, \qquad (1.1)$$

where H and R are in metres and the yield W in kilotons of TNT. The constant of proportionality in (1.1) diminishes as the water depth decreases and consequently the energy delivered to the water is greater at depth than for a shallow burst having the same yield. The empirical expression holds provided the depth of water d_w (metres), in which the surface waves are produced is in the range:

$$78\, W^{1/4} < d_w < 259\, W^{1/4}, \qquad (1.2)$$

where the lower limit is the maximum diameter of the gas bubble. The relation is valid for any depth of water in which an explosive device is detonated. The idealized surface displacement is shown in figure 1.

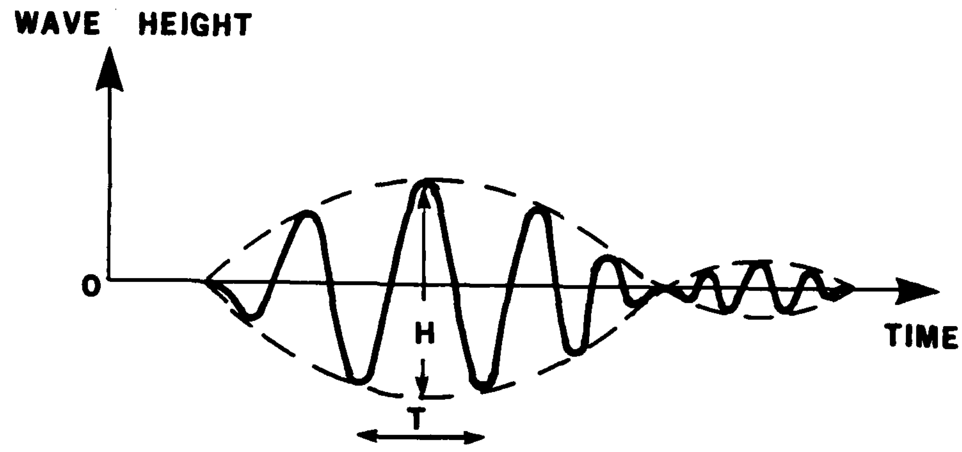

FIGURE 1 An explosion generated wave train as observed at a given distance from surface zero (Glasstone and Dolan (1977)).

A theoretical interpretation of the above wave structure presents some difficulties and this arises from the fact that to give a complete description of the phenomena would require details of the detonation, propagation of the shock and pulsating bubble as well as venting and blast effects. To include all these physical phenomena into a single set of equations in order to delineate the associated wave train would render the problem intractable analytically.

In this paper a mathematical model is developed which encompasses (i) the observations of waves generated at the Bikini nuclear test site in the Pacific Ocean (Glasstone and Dolan (1977)), and (ii) the wave structure that can be expected from a submarine volcanic explosion. We assume that the waves generated by the above phenonema are similar and can be treated by the same model. Moreover we consider a rigid cyclindrical volume of water to be projected vertically from a depth h_o, for infinite water above a rigid bottom with a known velocity under the action of ordinary forces. The method of approach will be to derive analytically a solution of the linearized wave equations for water of uniform depth, in the context of the linear theory of long waves (Whitham (1974)).

The above type of wave disturbance can also be attributed to tectonic plate uplifting of oceanic blocks leading to the formation of tsumani waves. Such problems are of interest in dynamical oceanography.

The waves generated by the above phenomena are also of interest in understanding the vulnerability of ocean as well as coastal structures to wave loading and inundation.

2. EQUATIONS OF MOTION

Consider an inviscid incompressible fluid in a constant gravitational field. A rigid cylinder of fluid of radius $0 < r < r_o$ is assumed to be projected upwards from a depth $z = -h_o$, to the plane of the undisturbed free surface $z = 0$ with a velocity $\xi(t)$ in the positive z direction, as shown in figure 2. It will be assumed that each element of moving fluid experiences no nett rotation from one instant to the next. Therefore the fluid is assumed to be irrotational, i.e. there is zero vorticity in the fluid. If u is the fluid velocity then curl$\underline{u}$ = 0. For irrotational flow we may write

$$\underline{u} = \nabla\phi, \tag{2.1}$$

where ϕ is the velocity potential and ∇ the gradient operator. For incompressible flow:

$$\nabla.\underline{u} = 0, \tag{2.2}$$

and substituting (2.1) into (2.2) gives:

$$\nabla^2\phi = 0, \tag{2.3}$$

that is the solution of the irrotational motion of the incompressible fluid satisfies Laplace's equation. This equation is to be solved on the boundary z=0, subject to application of an axisymmetric disturbance.

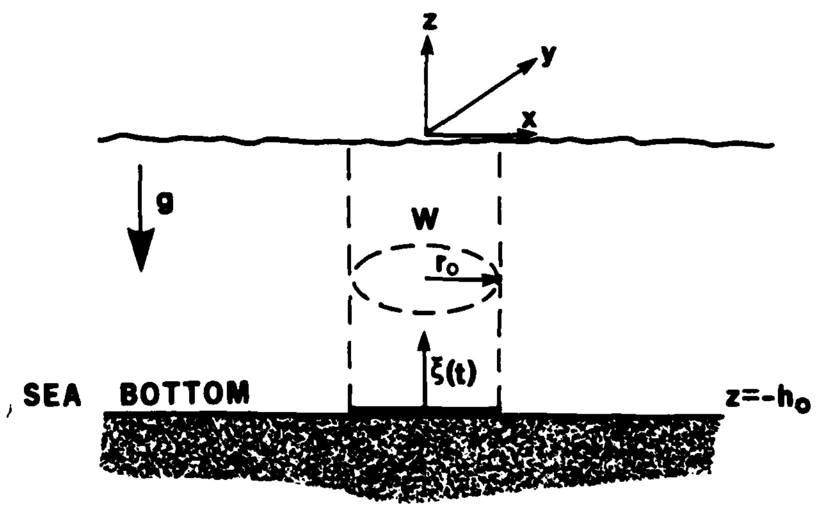

FIGURE 2 Physical configurations for a cylindrical volume of water (W) moved rigidly upwards.

Consider the case of a body of fluid with air above and describe the interface or the free surface by:

$$f(r,z,t) = \eta(r,t) - z = 0, \tag{2.4}$$

neglecting surface tension. f is a function which is always zero for a particle on the free surface. Any disturbance of the surface clearly implies some motion of the air and here we assume that the pressure in the air due to the motion is negligible and the air pressure may be approximated by its undisturbed value. The boundary conditions at the *undisturbed free surface* in the context of the linear theory can be written as (Whitham (1974)):

$$\eta_t = \phi_z, \tag{2.5a}$$

and $\qquad$ on $z = \eta(r,t)$,

$$\phi_t + g\eta = 0, \tag{2.5b}$$

where g is the gravitational acceleration. Differentiation with respect to t of the kinematic free surface condition (2.5b) and substituting (2.5a) into this expression, yields the following equation to be satisfied on the boundary $z = 0$:

$$\phi_{tt} + g\phi_z = 0 \; . \tag{2.6}$$

On the rigid boundary $z = -h_o$ the normal velocity of the fluid vanishes:

$$\underline{n}.\nabla\phi = 0, \tag{2.7}$$

where $\underline{n}$ is a vector normal to the surface. Thus the problem is to find a solution of Laplace's equation subject to the boundary conditions (2.5) and the initial conditions:

$$\phi(r,0,0) = 0, \tag{2.8a}$$

and

$$\phi_t(r,0,0) = 0. \tag{2.8b}$$

If h_o is the depth below the water surface at which the fluid disturbance originates, then a further condition on the velocity potential is:

$$\phi_z = \begin{cases} \xi(t) & r < r_o, \quad z = -h_o, \\ 0 & r > r_o \end{cases} \tag{2.9}$$

where the function $\xi(t)$ is related to the generating mechanism of the disturbance. In order to derive closed form solutions it is necessary to choose $\xi(t)$ appropriately, and this is further discussed in § 3.0. Once ϕ has been found subject to the above conditions the fluid surface elevation $z(r,t)$ is given by:

$$z(r,t) = \eta(r,t) = -\frac{1}{g}\,\phi_t(r,o,t). \tag{2.10}$$

3. SOLUTION BY METHOD OF INTEGRAL TRANSFORMS

A solution to Laplace's equation (2.3) subject to the above boundary and initial conditions can be found by employing the standard methods of integral transforms (Tranter (1971)). In the case of the present problem we firstly apply a Hankel transform to the radial coordinate r, followed by a Laplace transform on the time coordinate t.

(a) Hankel Transform

The Hankel transform $\overline{H}(\rho)$ of a function $H(r)$ is given by the integral:

$$\overline{H}(\rho) = \int_o^\infty H(r) r J_n(\rho r) dr, \tag{3.0}$$

where $J_n(\rho r)$ is the Bessel function of the first kind of order n. The inverse Hankel transform is given by:

$$H(r) = \int_o^\infty H(\rho)\rho J_n(\rho r) d\rho. \tag{3.1}$$

Laplace's equation (2.3) in cylindrical coordinates, the boundary conditions (2.6), the initial conditions (2.8) and the velocity potential (2.9) with n=0 in (3.0) can be expressed as:

$$\overline{\phi}_{zz} \quad \rho^2 \overline{\phi} = 0, \tag{3.2a}$$

$$\overline{\phi}_{tt} + g\overline{\phi}_z = 0, \tag{3.2b}$$

$$\overline{\phi}(\rho,0,0) = \overline{\phi}_t(\rho,0,0) = 0, \tag{3.2c}$$

and

$$\overline{\phi}_z = \begin{cases} \xi(t) \int_o^\infty r J_o(\rho r) dr, & r < r_o, \quad z = -h_o, \\ 0 & r > r_o \end{cases} \tag{3.2d}$$

on applying the transform (3.0). In taking the Hankel transform of (2.3) it has been assumed that $J_o(\rho r)$ satisfies the differential equation:

$$J_o''(\rho r) + (\rho r)^{-1} J_o'(\rho r) + J_o(\rho r) = 0,$$

where ( )' denotes differentiation with respect to ρr.

(b) Laplace Transformation

If we denote by $S^*(\alpha)$ the Laplace transform of a function $S(t)$, so that

$$S^*(\alpha) = \int_o^\infty S(t) e^{-\alpha t} dt, \tag{3.3}$$

then the operation of multiplying (3.2) by the kernel of the Laplace transform and integration with respect to t between o and ∞ leads to:

$$\overline{\phi}_{zz}^* - \rho^2 \overline{\phi}^* = 0, \tag{3.4a}$$

$$\alpha^2 \overline{\phi}^* + g\overline{\phi}_z^* = 0; \quad \text{on } z = 0, \tag{3.4b}$$

$$\overline{\phi}_z^{\,*} = \rho^{-1} r_o \xi^*(\alpha) J_1(\rho r_o); \quad r < r_o \text{ on } z = -h_o, \tag{3.4c}$$

where the initial conditions have been invoked in taking the Laplace transform of (3.4b). Furthermore the integral property of Bessel functions:

$$\int r^{\nu} J_{\nu-1}(r)dr = r^{\nu} J_{\nu}(r) + c,$$

has been used to rewrite (3.4c) in non-integral form. The problem is therefore reduced to finding a solution of (3.4a) subject to (3.4b) and (3.4c).

The appropriate solution of (3.4a) which satisfies (3.4b) and (3.4c) is:

$$\overline{\phi}^{\,*} = r_o \xi^*(\alpha) \frac{[\alpha^2 \sinh\rho z - g\rho \cosh\rho z]\, J_1(\rho r_o)}{\rho^2 [\sinh\rho h_o + \alpha^2 \cosh\rho h_o]}, \tag{3.5}$$

and for waves propagating on the surface, $(z = 0)$ (3.5) can be expressed as:

$$\overline{\phi}^{\,*}(\rho,o,\alpha) = \frac{-gr_o \xi^*(\alpha) J_1(\rho r_o)}{\rho[g\sinh\rho h_o + \alpha^2 \cosh\rho h_o]}. \tag{3.6}$$

The conversion of (3.6) to ϕ^* is accomplished by applying the formula (3.1):

$$\phi^*(r,o,\alpha) = -gr_o \xi^*(\alpha) \int_o^{\infty} \frac{J_1(\rho r_o) J_o(\rho r)\, d\rho}{\rho[g\sinh\rho h_o + \alpha^2 \cosh\rho h_o]}. \tag{3.7}$$

The inversion of (3.7) to $\phi(r,o,t)$ is *now accomplished* by the use of the inverse Laplace transform. Writing (3.7) as:

$$\phi^*(r,o,\alpha) = \xi^*(\alpha)\beta^*(\rho|\alpha), \tag{3.8}$$

where

$$\beta^*(\rho|\alpha): = -gr_o \int_o^{\infty} \frac{J_1(\rho r_o) J_o(\rho r)\, d\rho}{\rho[g\sinh\rho h_o + \alpha^2 \cosh\rho h_o]}, \tag{3.9}$$

and applying the Faltung theorem for Laplace transforms, the velocity potential is given by

$$\phi(r,o,t) = \int_o^t \xi(t-\lambda)\beta(\rho|\lambda)d\lambda, \tag{3.10a}$$

or alternatively,

$$\phi(r,o,t) = \int_o^t \xi(\lambda)\beta(\rho|t-\lambda)d\lambda. \tag{3.10b}$$

Substitution of (3.10a) (or (3.10b)) into (2.10) gives:

$$z(r,t) = -\frac{1}{g}\partial_t \phi(r,o,t) = -\frac{1}{g}\int_o^t \xi(\lambda)\partial_t \beta(\rho|t-\lambda)d\lambda + \xi(t)\beta(\rho|o), \tag{3.11}$$

for the free surface elevation. The partial derivative $\beta_t(\rho|t-\lambda)$ appearing in (3.11) can easily be evaluated and is:

$$\partial_t \beta(\rho|t-\lambda) = -gr_o \int_o^\infty J_1(\rho r_o) J_o(\rho r) \frac{\cos(\sqrt{\rho g \tanh \rho h_o}(t-\lambda))d\rho}{\cosh \rho h_o} . \tag{3.12}$$

Writing this integral as $\beta^+(\rho|t-\lambda)$ and substitution into (3.11) yields:

$$z(r,t) = -\frac{1}{g}\int_o^t \xi(\lambda)\beta^+(\rho|t-\lambda)d\lambda + \xi(t)\beta(\rho|o),$$

or from a change in variable:

$$z(r,t) = -\frac{1}{g}\int_o^t \xi(t-\lambda)\beta^+(\rho|\lambda)d\lambda + \xi(o)\beta(\rho|t). \tag{3.13}$$

Since ξ is by definition the response of the generating mechanism of the disturbance, which is initially passive, it follows that $\xi(o) = 0$. The second term appearing on the right side of (3.13) can therefore be neglected.

In general, integrals of the form (3.13) are intractable even for simple forms of $\xi(t-\lambda)$. If solutions are to be found it is necessary to resort to either asymptotic analysis or numerical integration.

One solution to (3.13) can be found if we suppose that the fluid is initially at rest in the region $|r| < a$, $z = -h_o$ and that at $t = 0$ an hydrodynamic axisymmetric impulse is delivered which generates the velocity potential (2.9). If this impulse acts only briefly then (2.9) can be replaced by a Dirac delta-function, that is we replace $\xi(t-\lambda)$ by $\delta(t-\lambda)$ in (3.13). Now (3.13) can be integrated provided β^+ is continuous at $t = \lambda$ and $o<\lambda<t$. This leads to the result:

$$z(r,t) = -\frac{1}{g}\beta^+(\rho|t),$$

or

$$z(r,t) = r_o \int_o^\infty J_1(\rho r_o) J_o(\rho r) \frac{\cos(t\sqrt{\rho g \tanh \rho h_o})d\rho}{\cosh \rho h_o} . \tag{3.14}$$

4. ASYMPTOTIC BEHAVIOUR

The integral in equation in (3.14) can be evaluated on applying the Kelvin principle of stationary phase, Whitham (1974). Firstly however (3.14) must be reduced to canonical form. For large values of α, $J_o(\alpha)$ is a fluctuating function which has an asympototic expansion:

$$J_o(\alpha) \sim \left(\frac{2}{\pi\alpha}\right)^{1/2} \cos\left(\alpha - \frac{\pi}{4}\right), \tag{4.1}$$

so for large values of r, equation (3.14) behaves asymptotically as:

$$z(r,t) \sim \frac{r_o}{\sqrt{2\pi r}} \mathrm{Re} \int_o^\infty \frac{J_1(\rho r_o)}{\sqrt{\rho \cosh \rho h_o}} \{e^{i(-t\sqrt{\rho g \tanh \rho h_o} + \rho r - \pi/4)}$$

$$+ e^{-i(t\sqrt{\rho g \tanh \rho h_o} + \rho r - \pi/4)}\} d\rho ,$$

and contains both outgoing waves and incoming waves. Since $r>o$, the main contribution in the case $t>o$ comes from the first term and represents waves propagating outward from the disturbance to infinity. For these waves the integral can be expressed as:

$$z(r,t) \sim \frac{r_o}{\sqrt{\pi r}} \mathrm{Re}\int_o^\infty \frac{J_1(\rho r_o)e^{-iX(\rho)t}}{\sqrt{\rho\cosh\rho h_o}} d\rho, \tag{4.2}$$

where

$$X(\rho) := W(\rho) - \rho r t^{-1} \ . \tag{4.3}$$

The frequency relation:

$$W(\rho) := \sqrt{\rho g \tanh \rho h_o} \ , \tag{4.4}$$

is the usual dispersion relation for gravity waves of the differential equation (2.3), where ρ is the wave number and has the following algebraic properties. If $\rho>0$, $W'(\rho)$ is a monotonic decreasing function and $W''(\rho)<0$. The waves propagate to the right with the phase speed:

$$c(\rho) = \frac{W(\rho)}{\rho} \ , \tag{4.5}$$

and group velocity

$$C(\rho) = D_\rho W(\rho) = \tfrac{1}{2}c(\rho)(1 + 2\rho h_o \operatorname{cosech}(2\rho h_o)) \ . \tag{4.6}$$

For the motions we are interested in, that is the behaviour for large r and t, the interesting limit is $t \to \infty$ with rt^{-1} held fixed. With (4.2) in canonical form for applying Kelvin's method of stationary phase the surface elevation is given by:

$$z(r,t) \sim \frac{r_o(\rho r t|W''(\rho)|)^{-1/2}}{2\cosh\rho h_o} J_1(\rho r_o)\cos(t\sqrt{\rho g\tanh\rho h_o} - \rho r), \tag{4.7}$$

where $\rho(r,t)$ is the positive root of

$$X'(\rho) = W'(\rho) - \frac{r}{t} = 0, \quad \rho>0, \quad \frac{r}{t}>0. \tag{4.8}$$

Scaling the independent variables as:

$$\rho \to k^* h_o^{-1}, \quad r \to r^* h_o, \quad t \to t^*(h_o g^{-1})^{1/2} \ , \tag{4.9}$$

the displacement of the surface can finally be expressed as,

$$z(r,t) \sim \left(\frac{W'(k)}{k|W''(k)|}\right)^{1/2} \frac{r_o J_1(kr_o/h_o)}{2h_o r\cosh k}\cos(t\sqrt{k\tanh k} - kr) \ , \tag{4.10}$$

after dropping the *. Since surface water waves can travel at a maximum velocity of $(gh_o)^{1/2}$ the water surface remains stationary until such time as a wave arrives and this event occurs when $t = r/\sqrt{gh_o}$. If $t<r/\sqrt{gh_o}$ then the surface is stationary and $z(r,t) = 0$, whilst if $t>r/\sqrt{gh_o}$, $z(r,t)$ is given by (4.10).

In terms of (4.3) and (4.4) equation (4.10) can be written

$$z(r,t) = \mathrm{Re}\{A(r,t)e^{iX(k)t}\}, \tag{4.11}$$

where the amplitude is:

$$A(r,t) = \left(\frac{W'(k)}{k\left|W''(k)\right|}\right)^{1/2} \frac{r_o\, J_1(kr_o/h_o)}{2h_o r\cosh k}\,. \tag{4.12}$$

The oscillating wave train represented by (4.11) has A, k and W as functions of r and t. In order to delineate graphically the wave train we take a particular value of k_o. Thus

$$r = \sqrt{gh_o}\, W'(k_o)t,$$

represents an observer moving with a velocity $W'(k_o)$ who observes a propagating wave with wave number k_o and frequency $W(k_o)$. If $r_o > h_o$, the wave profile is shown in Figure 3 a,b. The wave profiles are non-periodic with amplitudes decreasing to zero when either $J_1(kr_o/h_o) = 0$ or $\cos(t\sqrt{k\tanh k} - kr) = 0$, that is, when

$$\frac{r_o k}{h_o} = j_{1,s}\ ,$$

where $j_{1,s}$ are the zeros of J_1 (i.e., $j_{1,1} = 3.83171$, $j_{1,2} = 7.01559\ldots$)

or $$t = \frac{kr + \pi(n + 1/2)}{\sqrt{k\tanh k}}\,, \qquad n = 0,1,2,\ \ldots$$

Furthermore the amplitude of the group decreases as time advances from a maximum A_o to zero, then increasing to a new maximum $A_1 < A_o$, and so on. The time interval between wave crests at earlier times is longer than at latter times and the wave profile is equivalent to the one given in section 1, and represents a tsunami (Adams (1970)).

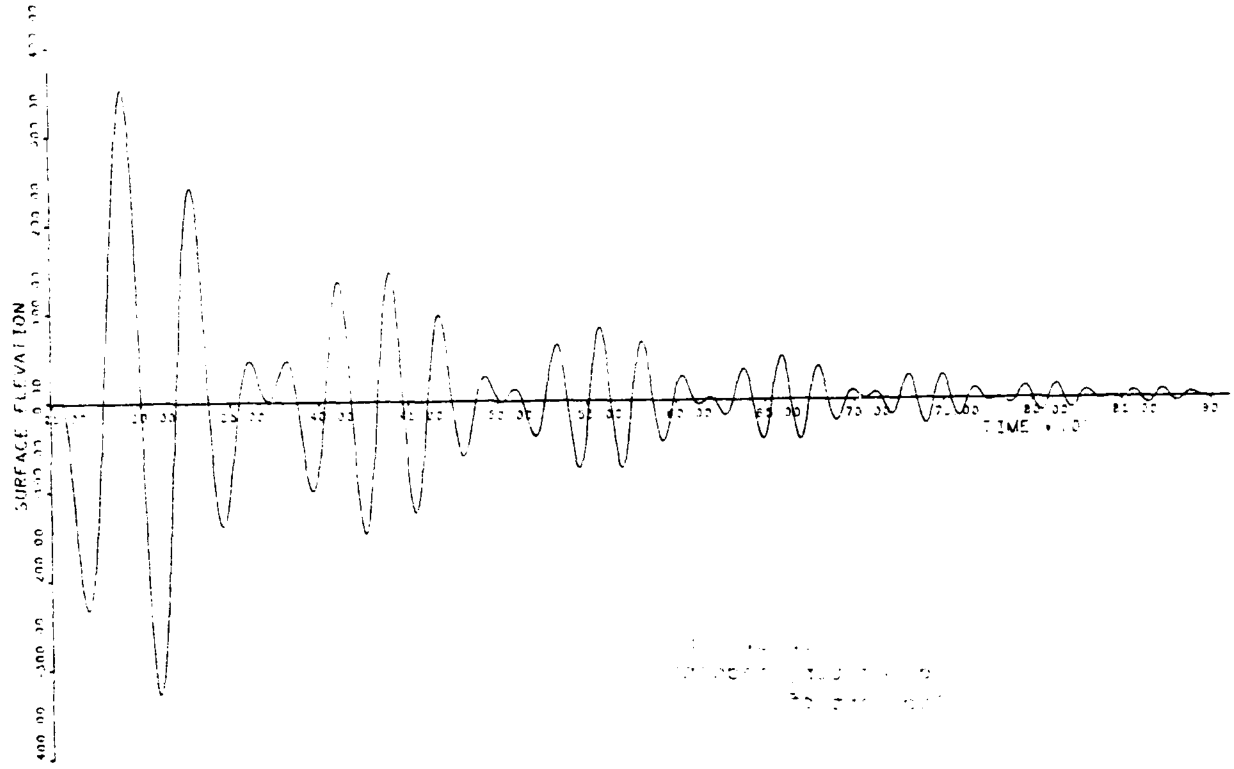

FIGURE 3a A section of the wave profile generated by a underwater disturbance at r=2000 for r_o=50, h_o=10.

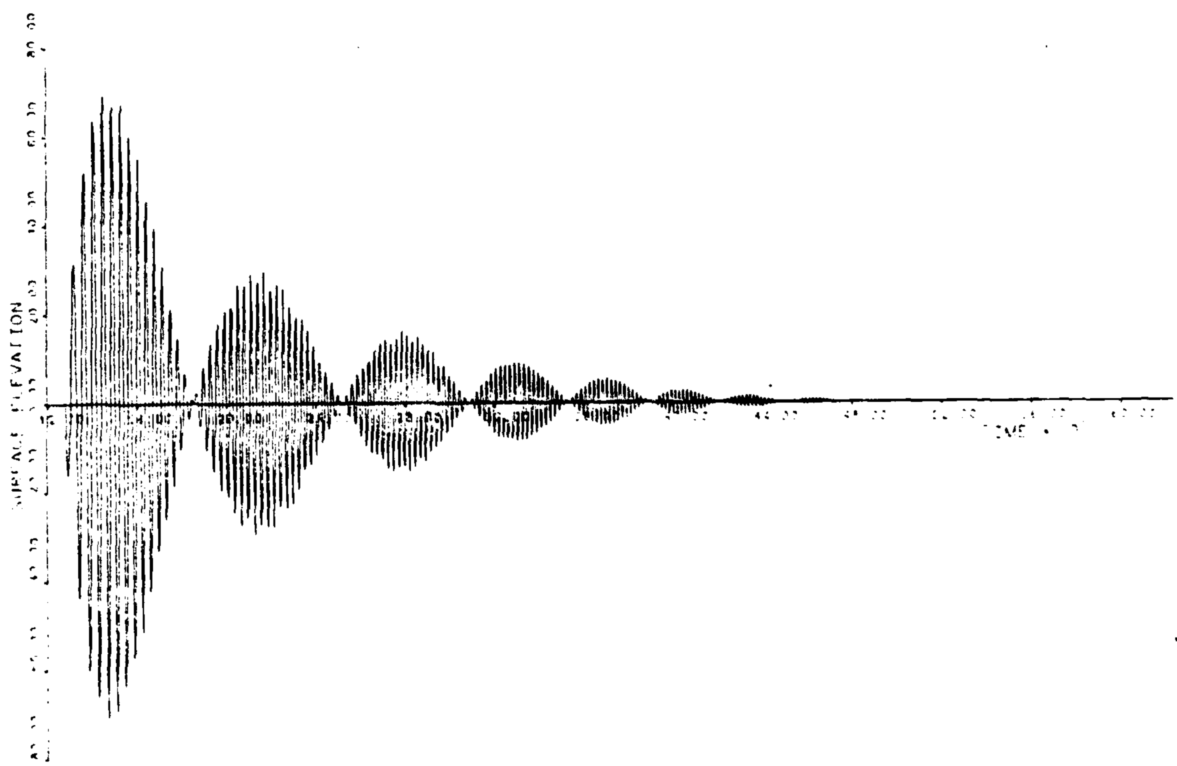

FIGURE 3b A section of the wave profile generated by a underwater disturbance at r=10000 for r_o=50, h_o=10.

5. CONCLUSIONS

The theoretical results shown in this report simulating tsuanami waves, and the observations made at the Bikini nuclear test site are in close agreement within the context of the linear theory of waves. The primary assumption employed in the theoretical analysis, that the disturbance can be represented by a Dirac-delta function, appears to be acceptable. Moreover the disturbance is represented mathematically by a vertical piston type action, where the piston represents the driving mechanism of the disturbance. This assumption is necessary if the analysis is to be tractable. Although the analysis employs asymptotic approximations the wave structure is representative of that given in Section 1 if $r_o > h_o$.

The analysis presented herein offers some insight into the structure of tsuanami waves generated as a consequence of either (i) a thermonuclear detonation, (ii) submarine volcanic explosion; or (iii) abrupt uplifting of a section of the seabed. The magnitude of the disturbance can be determined from the generating mechanism, the dimension of the area of origin, and depth and displacement of water.

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